Optical Sensors and 2D all Optical Memory - new Photonic Devices based on Plasmonic Resonance

Aurelian POPESCU
National Institute of R&D of Optoelectronics INOE 2000, 409 Atomistilor str.,Magurele, Romania
apopesku@inoe.ro

***Abstract* - In report is made the synthesis of the surface plasmon polariton propagation phenomenon. Methods such as Maxwell equations, Drude model used to describe the light confinement at the interface between two media are analyzed. Simulation techniques such as the transfer matrix formalism and the dispersion equation are examined. Finally are presented the results of our own investigations aiming plasmonic structure containing a film of amorphous chalcogenide material. It is shown the structure is very sensitive to the modifications of the refractive index that may be used for the design of the optical memory.**

***Index terms:* photonics, plasmonics, chalcogenide amorphous materials, optical memory.**

I. INTRODUCTION

The ability of light to transmit information is enormous, due to the fact that the light frequency as electromagnetic wave overpass 100.000 GHz. Beyond of this, in optics there exists the simple possibility of information parallel processing by Fourier transform with the aid of a lense. As to date the technology of the optical fibers fabrication with losses smaller then 0.2 dB/Km is already realized, it can be foresee the human desire to use the light as support for the transmission of information. Regrettably the photonic devices dimensions are restricted from the miniaturization point of view by the diffraction limit, these one being established for the conventional optical devices at a level of half of the wavelength. In the visible spectral range diffraction limit constitutes on cca 250 nm, which is very much when compared to the actual electronic components dimensions, and which have already reached values less then 100 nm.

In the actual stage, researchers develop a new technique of nanometric scale optical signals transmission. The modern beginning of this domain was put forward in the 1968 year, by Kretschmann and Raether [1], which purposed the method of plasmonic surface waves excitation. The surface plasmons represent waves of the electric charge density variation at the metal – dielectric interface. These excitations are intrinsically coupled with the electromagnetic waves, such that the light is forced to propagate along the metallic surface at small distances, beyond the wavelength. Due to the matching requirements, both the frequency and the propagation speed must correspond with those of the electromagnetic waves. The phenomenon was predicted at the beginning of the 20th century by Zenneck [2], and reffers to the problem of telegraphic signal propagation as radio waves which are described by the Maxwell equations.

The light attenuation in plasmonic structures is doomed to be relatively large. The propagation distance is usually lower then one millimeter, due to the fact that free electrons are forced by the electromagnetic field to oscillate. This inconvenience can be overpassed by the fact that the interaction of light with matter is realized even at lower dimensions, partially due to the large electric carriers concentration, which in metals is of the order of 10^{23}. The plasmon propagation can be used for the routing of the signals along the electric nanowires. The phenomenon takes place without charge displacement, such that the effects of inductance and capacity which reduce the integrate circuits capacity does not occur.

It is inconcevable to deal the plasmonics in all its complexity, because the application domains of plasmonics are very numerous. There are known in the literature much specialized monographs [3-6], on problems linked to plasmonics. An exhaustive analysis of the phenomena linked to the plasmonics frontiers ones, is presented in the Mihalache's review [7].

The aim of this paper constitutes on the presentation of an image regarding two directions of the plasmonics, which proved to be very close between them, namely the plasmonics sensors (especially the biosensors), and elements of optical memory and optical switchers. The apparition of bio -sensors on the market has patrimonial value too, because it served as an accelerator of the researche on the plasmonics field. So that, beginning from 20 years ago, the number of publications containing the terms ”surface plasmon resonance” doubles each five years, finding them ourdays on a number of 2000-3000, depending on the database accessed..

In order the phenomenon to be understood by the researchers which deal with other fields of physics and photonics technologies, at the beginning of this paper we shall present briefly the principles of which these above mentioned elements does function, as well as technical and technological methods used.

II. SURFACE PLASMON-POLARITONS (SPP), BASIC NOTIONS

2.1. SPP Wave equation and dispersion characteristics

SPP are electromagnetic excitations propagating along the interface between a conductor (usually metal) and a dielectric. These are surface electromagnetic waves that represent the coupling of the electromagnetic wave with the free oscillations of the electrical charges from the conductor. The equations which describe the fenomenon are derived from the Maxwell's equations. If the case of harmonic oscilations they reduce to the Helmholtz wave equation:

$$\nabla^2 \vec{E} + k_0{}^2 \varepsilon \vec{E} = 0 \qquad (1)$$

They are solved for different geometries in many books [8, 9, 10]. In the simplest case when the structure is infinite in the xy plane they reduce to the one dimensional case:

$$\frac{\partial^2 \vec{E}(z)}{\partial z^2} + \left(k_0{}^2 \varepsilon - \beta^2\right)\vec{E}(z) = 0 \qquad (2)$$

Were β is the propagation constant in the propagation direction x:

$$\vec{E}(x, y, z) = \vec{E}(z)\exp(i\beta x)$$

The equation above is a vectorial equation and, in the general case, is a system of three equations. Introducing the concept of TM mode, when the wave has only one magnetic component H_y (H_x=H_z=0) and TE mode when the wave has only one electric component E_y (E_x=E_z=0) allows us to reduce the system to a scalar one:

$$\frac{\partial^2 E_y}{\partial z^2} + \left(k_0{}^2 \varepsilon - \beta^2\right)E_y = 0 \quad . \qquad (3)$$

For the magnetic field the equation is practically the same.

In the simplest case when the geometry represents the interface of two semi-infinite media with dielectric constants ε_1 and ε_2 the solutions are seeked on exponential form for each medium. After the application of the boundary conditions the following equality is obtained:

$$\frac{k_2}{k_1} = -\frac{\varepsilon_2}{\varepsilon_1}$$

Were $k_1{}^2 = \beta^2 - k_0{}^2 \varepsilon_1$ and $k_2{}^2 = \beta^2 - k_0{}^2 \varepsilon_2$ (4)

By replacing k_1 and k_2 the central result of the SPP, the dispersion (or characteristic) equation leads:

$$\beta = k_0 \sqrt{\frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2}} \qquad (5)$$

Two conditions are needed in order the metal-dielectric interface supports SPP [9]:

a) Surface plasmon polaritons exist only for TM polarization.

For this polarization the electric field have its component perpendicular to the interface dielectric-metal, that can cause the oscillation of free electrons. No surface modes exist for TE polarization.

b) The real parts of the dielectrics constant of the metal ε_{1r} and dielectric ε_2 are of opposite sign and satisfy the conditions: Re $\{\varepsilon_{1r}\} < -\varepsilon_2$.

The electromagnetic field decreases exponentially when departing from the interface. The penetration depth is around ½ of the wavelength in dielectric (that is 250-300 nm) and 10-15 nm in metal, such as the electromagnetic field can propagate along the free metal surface, being strongly confined.

2.2. Optical constant of metals

Metal-dielectric separation surface supports SPP only for conducting media which have the dielectric constant of a large enough value. An appropriate model should be formulated to calculate the dielectric constant and its dependence on frequency.

The optical properties of metals can be understood by treating the metals as a gas of free electrons which moves against a fixed positive ion cores. This model is named plasma model and may be described by the Newton equation of motion [8]. The resulting oscillation of the electrons causes macroscopic polarization which when using the constitutive Maxwell's relations D = εE lead at the desired result:

$$\varepsilon(\omega) = 1 - \frac{\omega_p{}^2}{\omega^2 + i\gamma\omega} \qquad (6)$$

Were

$$\omega_p = \sqrt{\frac{ne^2}{\varepsilon_0 m}}$$

is the plasma frequency which depends of the electronic concentration *n* and the effective mass of the electron *m.*

As we can see the dielectric function $\varepsilon(\omega) = \varepsilon_r(\omega) + j\varepsilon_i(\omega)$ have real and imaginary components. For large enough frequencies $\omega \gg \gamma$, but $\omega < \omega_p$, the dielectric constant ε(ω) is both real and negative:

$$\varepsilon(\omega) = 1 - \frac{\omega_p{}^2}{\omega^2} \qquad (7)$$

However the frequency dependence differs significantly for real metals, especially for the nobil metals mainly used in the plasmonic experiments. Tabulated values exist for the optical constant, to see the Handbook of Palik [11, 12].

Table1. Optical constants of metals

Metal	Wave-length, μm	Refrac. index	Extinct. coeff.	Complex dielectric constant
Au	0.653	0.166	3.15	-9.89 - j1.05
Au	1.55	0.550	11.5	-132 - j12.6
Ag	0.653	0.140	4.15	-17.2 - j1.16
Ag	1.55	0.514	10.8	116 - j11.1
Al	0.653	1.49	7.82	-58.9 - j23.3
Al	1.55	1.44	16.0	-254 - j46.1

Several examples extrapolated to the lasers wavelengths are presented below. The dielectric constant is calculated as $\varepsilon(\omega) = (n - jk)^2$.

To mention the higher values of the extinction coefficient for aluminium from the table above, lead to the higher attenuations of SPP's waves. For this reason the noble metals are the better materials for realising plasmonic interactions.

2.3. Excitation of SPP by prism method

The short analyse provided above lead us to the dispersion equation for the plasmon propagation constant.

This is the SPP wave that our structure suppports. In order to excite such waves, the phase-matching conditions for energy and momentum must be ensured. This is not a trivial case since the propagation constant β is greater than the wave vector k of the light in the dielectric. Different techniques for SPP excitation were proposed in order to increase the value of the light wave vector. The first one was purposed by Kretschmann and Raether [1]. They proposed and demonstrated that phase-matching conditions can be achieved by using a thin metal film in a three-layer configuration. The top layer is made of a dielectric with the refractive index higher than the bottom one. SPP is excited at the bottom metal interface via the evanescent waves (Fig.1).

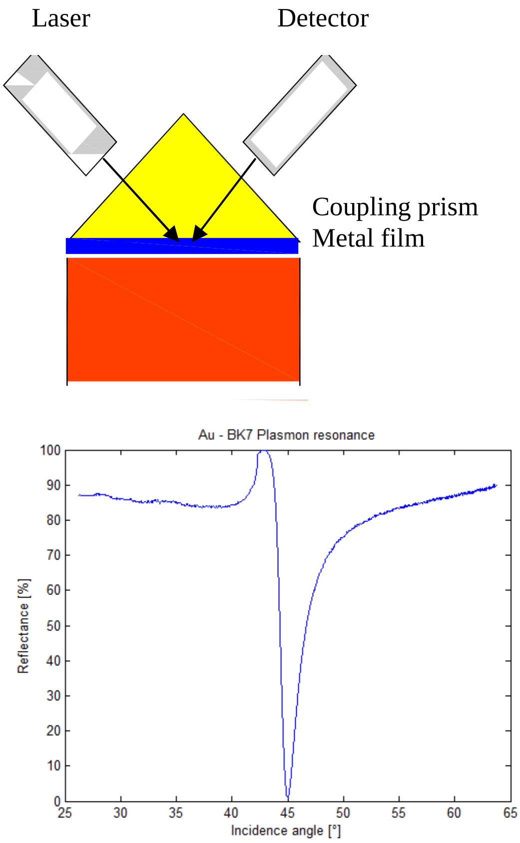

Fig.1. Schematic presentation of surface plasmon resonance (Kretschmann configuration) on the top side and the experimental resonance curve with gold film at the bottom side. The metal film thickness is 50 nm.

The propagation constant β which is defined by from the formula (5) must be equal to the tangential to surface component of the light wave vector:

$$k_o n \sin\Theta = \beta = k_0 \sqrt{\frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2}} \qquad (8)$$

In the formula above deduced for the propagation constant for a single interface it is tacitly assumed the metal film to be thick.

When the film becomes to have lower thickness, the SPP's modes begin to couple between them, thus producing a shift of the resonance angle. Thes shift was calculated fot the first time by Kretschmann [13]. The shift of the resonance curve is small when the film has about 50 nm thickness coresponding on the optimal dip in reflectance. The exact solution for the propagation constant of metallic film located between two semi-infinit dielectrics corresponding to the three-layer Kretschmann configuration is obtained as a transcendental equation which can be solved numerically using solver for complex numbers. In the book of Sophocles [14, Ch.09] we can find the solutions for many three-layers plasmonic waveguide configurations. The dielectric with higher real dielectric constant must have a prismatic form which ensures the conditions of directing light to higher incidence angles.

The analytical expression for the reflectivity curve like the experimentally measured one presented in fig.1 (right) is given in book [15, Ch.14] and represents the Airy formula for the three-layer structure. We'll not meet reflectivity formula for structures of more layers, because it could become too complicated. Abeles's 2x2 matrix approach [16] is welcome for calculation of the optical reflectivity in a multilayer structure. The field amplitudes connections between the first boundary and the last one may be descibed by the total characteristic matrix which is calculated as the multiplication of characteristic matrices with known coefficients [9].

III. OPTICAL SENSORS BASED ON SURFACE PLASMON RESONANCE (SPR)

As was established before, SPP are modes of the electromagnetic field confined near the metal-dielectric surface. The reflectance of light supports a dip and sharp resonance minimum (Fig.1) at a certain angle. The dip value and position depend on the optical constants of the metal and dielectric. We can consider the metal optical properties as being constant. Thus, the SPR angle depends only on the dielectric constants connected to the complex refractive index by the relation $\varepsilon = (n - jk)^2$. The other particularity that can be mentioned is the sensibility only to the properties of the medium situated close to the interface. This phenomenon can be used to create sensing optical device.

One of the first plasmonic sensors was a one designed for gas detection [17]. Since than sensors of others physical and chemical quantities were developed. The proposal of a plasmonic bio-sensing was especially succesfull, allowing the real time study of biomolecular interactions. It was one of the most investigated photonic devices.

The sensor technology has been commercialized by several companies such as BIACORE (Sweden), Texas Instrument (USA), Xantec (Germany) and others. SPR optical sensor comprises an optical system, a transducing medium (sensing chipset) and an electronic system. The Kretschmann geometry of ATR method has been found to be most suitable for sensing. The gold film with the thickness of 50 nm is the most common used. The films are obtained by the electron beam evaporation on the glasses slides covered with a thin 25 nm layer of chromium or titanium both to improve adhesion and to avoid the native properties of noble metal to form islands. The slides are put in optical contact with the prism by using immersion oil.

The sensitivity of SPR sensors to the refractive index changes was investigated by different authors [18-21]. The sensitivity to the refractive index changes was found to be of the order of 10^{-6}, which is very impressive when compared to the results obtained by interference methods, especially taking into account the submicronic optical interactions length. Many chemical sensors are based on the adsorption of analite molecules on the sensor surface. This one produces a local change of the refractive index which conducts to the changes of the resonance angle [22-25]. The changes in the reflected light are measured with a photodiode and related electronics.

IV. PLASMONIC 2D OPTICAL MEMORY WITH ACTIVE CHALCOGENIDE GLASS LAYER

Foreword: The chalcogenide phase-change materials are the key point for optical data storage in rewritable CDs and DVDs. A laser is used to thermally transform regions of the material from an amorphous to a crystalline state. Blue-ray disks have the capacity to store 25 Gigabytes, almost six times greater that of a DVD and equivalent to roughly 38 CDs. Further improvements in data storage lifetime and density will require, however, a comprehensive understanding of how the atomic make-up is altered by the laser light. Chalcogenide glass (ChG) compounds have characteristics of easy transition from crystalline state to amorphous state. The phase-change optical memory has amazing potential capacity up to 10 GB/cm2. However the write/erase process has some intrinsic time limit due to cooling rate restrictions.

All-optical memory may be realised by using photo-induced optical changes that occurs in thin films of semiconductor chalcogenide glasses (ChG) by irradiation with light. In order the phenomenon to be produced the photon energy must be higher than the semiconductor band gap energy. It is the region of fundamental optical absorption and the film thickness must be less than 1 µm. The phenomenon is reversible in some conditions [26-30]. The optical state of material is sensed with other light ray with lower photon energy at which the film is optical transparent. The value of the refractive index changes is rather small, of the order of 0.002 in As_2S_3, suggesting that interferometric methods usually used for the refractive index measurements are not very useful.

The chalcogenide films which exhibit changes of the properties under irradiation can be used as active layer with higher sensibility in SPR configuration. This is a novel light-material interaction configuration which recently has been demonstrated [31]. The use of a rutile prism with high refractive index leads to some limitations of the method. As in the case of plasmonic sensors, any change in the refractive index inside of the chalcogenide dielectric film causes a shift in the value of resonance angle, which is vary narrow. The phenomenon is widely used in plasmonic optical sensors. However, in our case the plasmonic structure becomes a 4-layer one that requires new calculations to be performed. The developed type of optical memory is a novel approach using the well known SPR method combined with an active ChG film. Our experience [32-37] in the physics and technology of ChG, denotes that under certain conditions permanent photoinduced changes of the optical absorption and of the refractive index occur in ChG thin films.

V. RESULTS

Four layers plasmonic configurations containing Prism-Gold film-Chalcogenide film-Air were realised. An additional thin dielectric ChG film was deposited on the chipset which contains a 50 nm gold film deposited on the glass slide. The calculations were done analitically by using a 2x2 matrix transfer formalism. The explicit results which conduct to the establishement of resonance angles values are easy to obtain for an arbitrary number of layers.

In recent works [38, 39] we have shown the advantages of light modulation in SPR configuration, which realises coupling of plasmon wave with waveguide modes. As the refractive index of the chalcogenide materials has high value (2.45–2.50) for As_2S_3 and GaLaS, they constitute a planar waveguides.

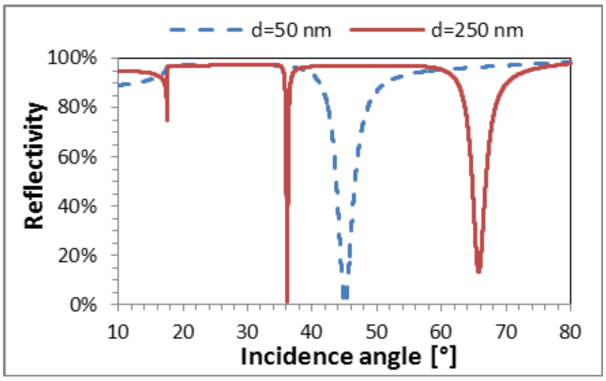

Fig.2. Simulations results for the TM modes. Plasmon (blue dashed curve) resonances and planar waveguide resonances (red curves) may be distinguished.

The resonance property and the sensibility to the refractive index change in a 4-layer structure which contains chalcogenide films were studied. The software for numerical SPR calculations for four layer structure was developed. The results are presented in in fig. 2.

For low thicknesses the resonance angle lowers up to 20-30° which corresponds to waveguide modes. This means that more convenient silica or borosilicate glass can be used as prism material. The mode coupled resonances are sharper than plasmon-polariton modes.

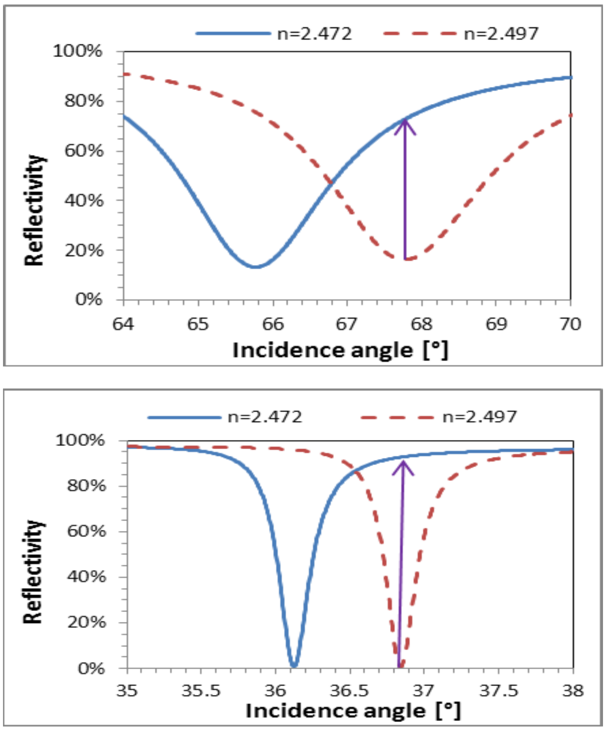

Fig.3. Change of the plasmon resonance angle value due to 1% modification of the refractive illustrates higher

sensitivity of the coupled plasmon-waveguide modes (bottom) compare to plasmonic resonances (top).

Such peculiarity can provide a greater sensitivity. The picks shift $\Delta\Theta/\Delta nf$ due to changes of the film refractive index were calculated and the results are presented below in fig. 3.

VI. CONCLUSIONS

The shifts of the reflectivity dip which corresponds to two values of film refractive indices, which differ by only 1%, are very distinctive. Simulations are done for p-polarised plasmonic mode (Fig.3, left) and for coupled waveguide mode (Fig.3, right). It can be seen that for the bounded plasmon-waveguide modes the same variation of the film refractive index is better distinguished. To find more features, the system of equations wich contains the field distributions were solved for four layer structure by applying the boudary conditions.

In the report an overall analysis of phenomena related to plasmon resonance and its applications as sensors (gas, chemical, bio-). Only an initiation to the optical plasmonic memory was done as the domain is very new. The references are done to our results, which exploits the photoinduced phenomenon in amorphous chalcogenide films. The four layer plasmonic configuration which contains active planar waveguide is more sensitive compared to the plasmon resonance. The methods and tools used to describe this phenomenon were synthetisized.

Many others, very amazing applications of plasmonic such as photonic nano-circuits, nonlinear very fast switchs, sub-wavelength imaging, slow light phenomena and so one remained out of our discussion. Plasmon is the bridge between the photonics and nanoelectronics. New achievements are foreseen in the field of photovoltaic cells. Plasmonics is an area that deserves our attention.

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REFERENCES

[1] E. Kretschmann and H. Raether, "Radiative decay of non-radiative surface plasmons excited by light", Z. Naturforschung, Vol. **23 A**, 2135-2136 (1968).

[2] J. Zenneck, "On the propagation of plane electromagnetic waves along a planar conductor surface and its relationship to wireless telegraphy", Ann Phys. Vol. **23**, 848 (1907).

[3] Chin-Lin Chen, "Foundations for guided-wave optics", John wiley & sons, Inc., (2007).

[4] Chris D. Geddes (Editor), "Reviews in Plasmonics 2010", Springer New York, (2010).

[5] Jiˇrí Homola (Volume Ed.), "Surface Plasmon Resonance Based Sensors", Springer-Verlag, (2006).

[6] R.B.M. Schasfoort and Anna J. Tudos (Editors), "Handbook of Surface Plasmon Resonance", The Royal Society of Chemistry, (2008).

[7] D. Mihalache, "Recent trends in micro- and nanophotonics: A personal selection", J. Optoelectron. Adv. Mater., Vol. **13**, No. 9, 1055-1066, (2011).

[8] Stefan A. Maier, "Plasmonics: Fundamentals and Applications", Springer, (2007).

[9] Zalevsky, Ibrahim Abdulhalim, "Integrated Nanophotonic Devices", 2nd ed., William Andrew, (2014).

[10] D. Marcuse, "Theory of dielectric optical waveguides", 2nd ed., Academic Press, Inc., (1991).

[11] E. D. Palik, "Handbook of Optical Constants of Solids I", New York, Academic Press, (1985).

[12] E. D. Palik, "Handbook of Optical Constants of Solids II", New York, Academic Press, (1991).

[13] Kretschmann E., Die Bestimmung optischer Konstanten von Metallen durch Anregung von Oberflächenplasmaschwingungen. Z. Physik, **241**: 313–324 (1971).

[14] Sophocles J. Orfanidis, Electromagnetic Waves and Antennas, http://www.ece.rutgers.edu/~orfanidi/ewa/.

[15] Max Born and Emil Wolf, "Principles of optics", 7th ed., Cambridge University Press, (1999).

[16] H.A. Macleod, "Thin-film Optical Filters", McGraw Hill, New York, (1988).

[17] C. Nylander, B. Liedberg, T. Lind, "Gas detection by means of surface plasmons resonance", Sensors and Actuators, **3**, 79–88 (1982).

[18] Jiří Homola, Sinclair S.Yee, Günter Gauglitz, "Surface plasmon resonance sensors: review", Sensors and Actuators B: Chemical, **54** (1-2), 3-15 (1999).

[19] R.P.H. Kooyman, H. Kolkman, J. van Gent, J. Greve, "Surface plasmon resonance immunosensors: sensitivity considerations", Anal. Chim. Acta **213**, 35–45 (1988)

[20] E.M. Yeatman, "Resolution and sensitivity in surface plasmon microscopy and sensing", Biosensors Bioelectron. **11**, 635–649 (1996).

[21] J. Homola, "On the sensitivity of surface plasmon resonance sensors with spectral interrogation", Sensors and Actuators B **41**, 207–211 (1997).

[22] M. Niggemann, A. Katerkamp, M. Pellmann, P. Bolsmann, J. Reinbold, K. Cammann, "Remote sensing of tetrachlorethene with a micro-fiber optical gas sensor based on surface plasmon resonance", Sensors and Actuators B **34,** 328–333 (1996).

[23] A. Abdelghani, J. M. Chovelon, N. Jaffrezic-Renault, C. Ronot-Trioli, C. Veillas, H. Gagnaire, "Surface plasmon resonance fiber-optic sensor for gas detection", Sensors and Actuators B **38–39**, 407–410 (1997).

[24] R.P. Podgorsek, T. Sterkenburgh, J. Wolters, T. Ehrenreich, S. Nischwitz, H. Franke, "Optical gas sensing by evaluating ATR leaky mode spectra", Sensors and Actuators B **39,** 349–352 (1997).

[25] E.G. Ruiz, I. Garcez, C. Aldea, M.A. Lopez, J. Mateo, J. Alonso-Chamarro, S. Alegret, "Industrial process sensor based on surface plasmon resonance (SPR): distillation process monitoring", Sensors and Actuators A **37–38** 221–225 (1993).

[26] M. Wittig, and N. Yamada, "Phase-change materials for rewriteable data storage", Nat. Mater., **6**(11), 824–832 (2007).

[27] A. V. Kolovos, P. Funs, A. I. Freckle, A. L. Ankudinov, J. Tominaga, and T. Uruga, "Understanding the phase-change mechanism of rewritable optical media", Nat. Mater**. 3**(10), 703–708 (2004).

[28] D. Lencer, M. Salinga, B. Grabowski, T. Hickel, J. Neugebauer, and M. Wuttig, "A map for phase-change materials", Nat. Mater. **7**(12), 972–977 (2008).

[29] Matsunaga T., et al., "From local structure to nanosecond recrystallization dynamics in AgInSbTe phase-change materials", Nature Materials, Vol.**10**(2), 129-134, (2011).

[30] Kotaro Makino, Junji Tominaga, and Muneaki Hase, "Ultrafast optical manipulation of atomic arrangements in chalcogenide alloy memory materials", Optics Express, Vol. **19**(2), 1260 (2011).

[31] Samson Z.L., Yen S.C., MacDonald K.F., Knight K., Li S.F., Hewak D.W., Tsai D.P., Zheludev N.I., "Chalcogenide glasses in active plasmonics, Physica Status Solidi-Rapid Research Letters", Vol. **4**(10), 274-276 (2010).

[32] A. Popescu, D. Savastru, S. Miclos, "Refractive index anisotropy in non-crystalline As_2S_3 films", J. Optoelectron. Adv. Mater., V.**12**(5), 1012-1018 (2010).

[33] A. Popescu, D. Savastru, M. Ciobanu, S. Miclos, V.T. Dolghier, "Mass-spectrometric studies of vitreous As_2S_3", J. Optoelectron. Adv. Mater., V.**13**, No.9, 1193-1198 (2011).

[34] A. A. Popescu, D. Savastru, S. Miclos, "Design and realization of low losses chalcogenide AsxS1-x planar waveguides", J. Optoelectron. Adv. Mater., V.**13**, No.3, 213-217 (2011).

[35] A. A. Popescu, D. Savastru, S. Miclos, V. Braic, M. Popescu, A. Manea, A. Kiss, "Properties of rare earth Ga-La-S glasses obtained by RF inductor heating", Dig. J. Nanomater. Biostruct., V.**6**, No.2, 341-348 (2011).

[36] M. Popescu, A. Velea, A. Lőrinczi, M. Zamfirescu, F. Jipa1, S. Micloş, A. Popescu, D. Savastru, "Two dimensional photonic structures based on as-s chalcogenide glass", Dig. J. Nanomater. Biostruct., V.**5**, No.4, 1579-1582 (2010).

[37] A. A. Popescu, R. Savastru, D. Savastru, S. Miclos, "Application of vitreous As-S-Se chalcogenides as active layer in surface plasmon resonance configuration", Dig. J. Nanomater. Biostruct, V.**6**(3), 1245-1232 (2011).

[38] Georgiana C. Vasile, Aurelian A. Popescu, Mihai Stafe, S.A. Koziukhin, Dan Savastru, Simona Donțu, L. Baschir, V. Sava, B. Chiricuță, Mona Mihăilescu, Constantin Neguțu, Niculae N. Puşcaş, "Plasmonic waveguides features correlated with surface plasmon resonance performed with a low refractive index prism", U.P.B. Sci. Bull., Series A, Vol. **75**(4), 311-325 (2013).

[39] Georgiana C.Vasile, Roxana Savastru, A.A. Popescu, M. Stafe, D. Savastru, Simona Dontu, L. Baschir, V. Sava, B. Chiricuta, M. Mihailescu, C. Negutu and N.N. Puscas, "Modelling the 2D plasmonic structures with active chalcogenide glass layer", Rom. Rep. Phys., Vol. **65**(3), 1012-1018 (2013).